Dark Energy and the Accelerating Universe

Brightness of distant Type Ia supernovae, along with CMB and galaxy clustering data, indicates the expansion of the Universe is accelerating, not decelerating.

This requires *either* a new form of stress-energy with <u>negative effective pressure</u> *or* a breakdown of General Relativity at large distances:

DARK ENERGY

Characterize by its effective equation of state:
and its relative contribution to the present density of the Universe:

$$w = p/\rho$$

Ω_{DE}

Note: $w < -1/3$, and can depend on time

The Dark Energy Survey in Context

- **Connecting Quarks with the Cosmos, Beyond Einstein, Quantum Universe, Physics of the Universe, HEPAP, DOE OS Facility Plan, …**

  - All identified Dark Energy as one of the most profound questions in fundamental physics, ripe for experimental progress

  - Endorsed a multi-pronged approach to dark energy from ground- and space-based telescopes

  - To make progress in understanding Dark Energy, we must reach greater precision: determine Ω_{DE}, $w = p/\rho$, and its evolution

Probing Dark Energy

- Probe dark energy through the history of the expansion rate:

$$H^2(z) = H^2_0 \; [\Omega_M (1+z)^3 + \Omega_{DE} (1+z)^{3(1+w)}] \qquad \text{(flat Universe)}$$

$$\text{matter} \qquad\qquad \text{dark energy}$$

- Comoving distance: $r(z) = \int dz/H(z)$
- Standard Candles $d_L(z) = (1+z)\, r(z)$
- Standard Rulers $d_A(z) = (1+z)^{-1}\, r(z)$
- Standard Population $dV/dzd\Omega = r^2(z)/H(z)$
- The rate of growth of structure also det'd by $H(z)$

The Dark Energy Survey

- Study Dark Energy using
  4 complementary techniques:
  - Cluster counting w/ SPT
  - Weak lensing
  - Galaxy clustering
  - SNe Ia distances

- Two multiband surveys:
  - 5000 deg^2 g, r, i, z
  - 40 deg^2 repeat (SNe)

- Build new 3 deg^2 camera
  - Construction 2004-2008
  - Survey 2008-2013 (600 nights)
  - Response to NOAO AO

Blanco 4-meter at CTIO

Science goal: w to ~5-10%

The Dark Energy Survey in Context: Toward A U.S. Dark Energy Program

- Coherent program aimed at increasing Dark Energy precision over the next ~15 years desirable

  - Sequence of logical, incremental steps of increasing scale, technical complexity, and scientific reach

  - Increase precision in w from ~20% today* to ~ few % (robustly) over this period. Determine evolution dw/dz to ~30%.

  - DES as logical next step in Dark Energy measurements beyond current surveys

  *Note: all quoted errors on w will assume it does not evolve
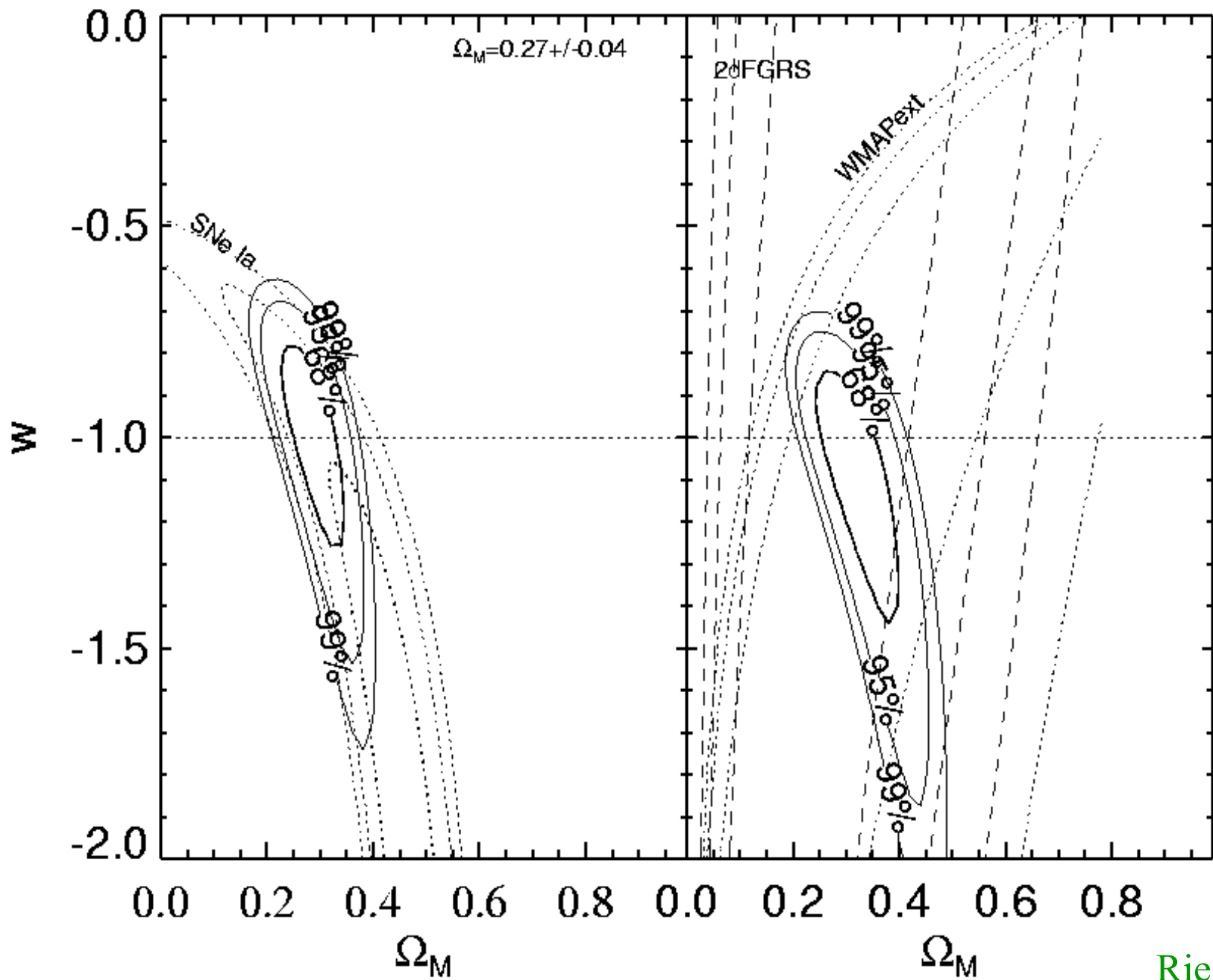
Dark Energy: where we are now
$\sigma(w) \sim 0.15*, \ w < -0.76$ (95%) with priors
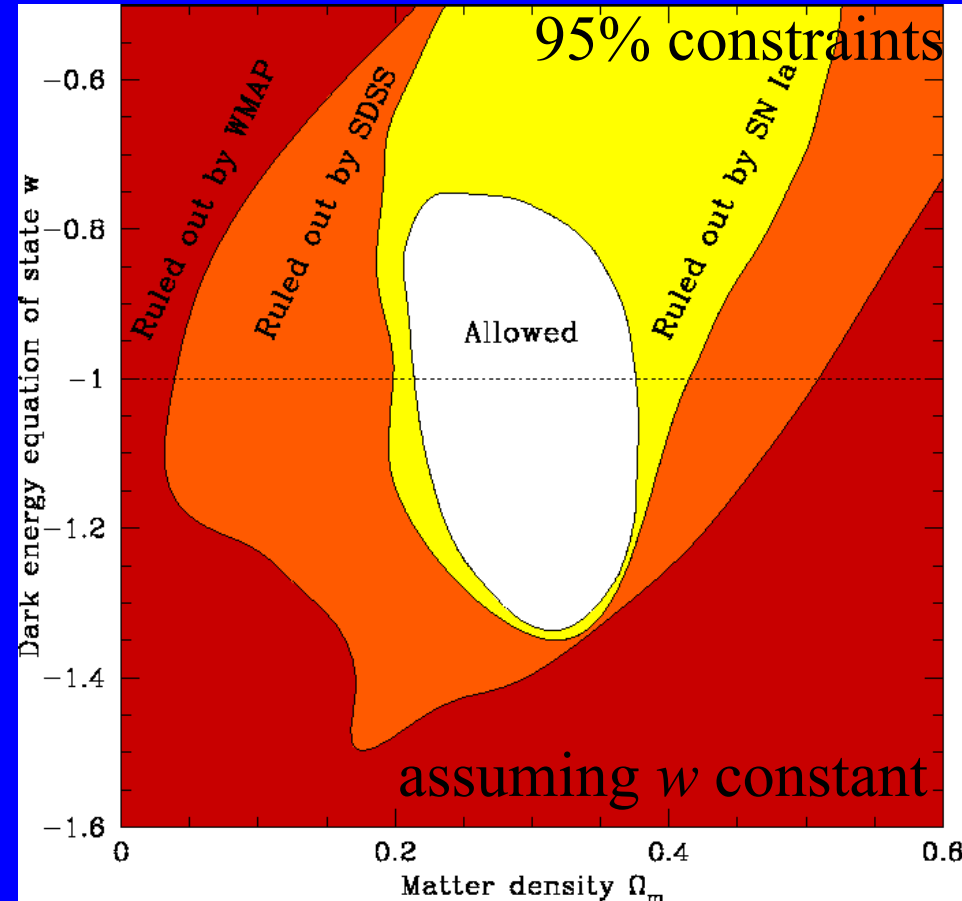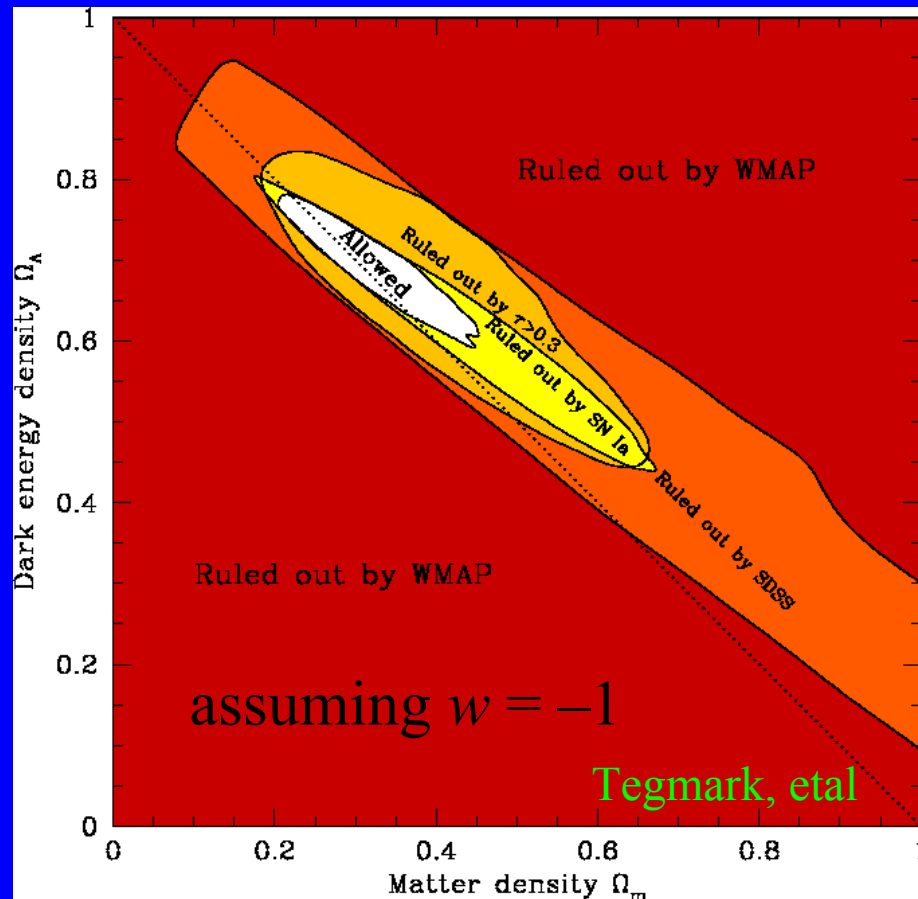
Key priors: scale-free spectrum, no gravity waves, massless neutrinos

Additional prior: flat Universe

*from CMB+LSS+SNe; no *single* dataset constrains *w* better than ~30%

Riess, etal

Dark Energy: 2004-2008
$\sigma(w) \sim 0.1$*

- Supernovae:

  ESSENCE, CFHTLS, HST, SNF, SDSS,…

  many 100's of SNe Ia over z ~ 0.1-0.8

- Weak Lensing:

  Deep Lens, CFHTLS, RCS II, …

  ~200-1000 sq. deg. deep multi-band imaging

- Cluster SZ:

 APEX, …   ~200 sq. deg. survey

*SNE+WMAP combined

The Dark Energy Survey in Context: 2008-2013

- DES as logical next step in dark energy measurements:

  - Will measure w to ~ 0.05–0.15 *statistical* accuracy* using <u>multiple complementary</u> probes, and begin to constrain *dw/dz*

  - Scientific and technical precursor to the more ambitious Dark Energy projects of the following decade: LSST and SNAP (2013+) (at a small fraction of the cost)

  - DES in unique position to synergize with SPT on intermediate timescale (PanSTARRS too far north)

  - *Cannot* be done with any existing or near-term facility: Blanco+DECAM ~5 times faster survey instrument than CFHT+Megacam, and >10x faster than any current U.S. facility

  *Note this is the accuracy on each probe *separately*, with no or at most weak priors.

Cluster Counts: SPT Synergy

- Probe dark energy through volume & growth of structure

- SPT will survey ~30,000 clusters over 4000 deg^2 using SZE

- DES will provide photometric redshifts for SPT clusters and independent cluster mass estimates (richness, lensing)

- Complementary to SNe constraints

SPT (self-calibrating)
WMAPext
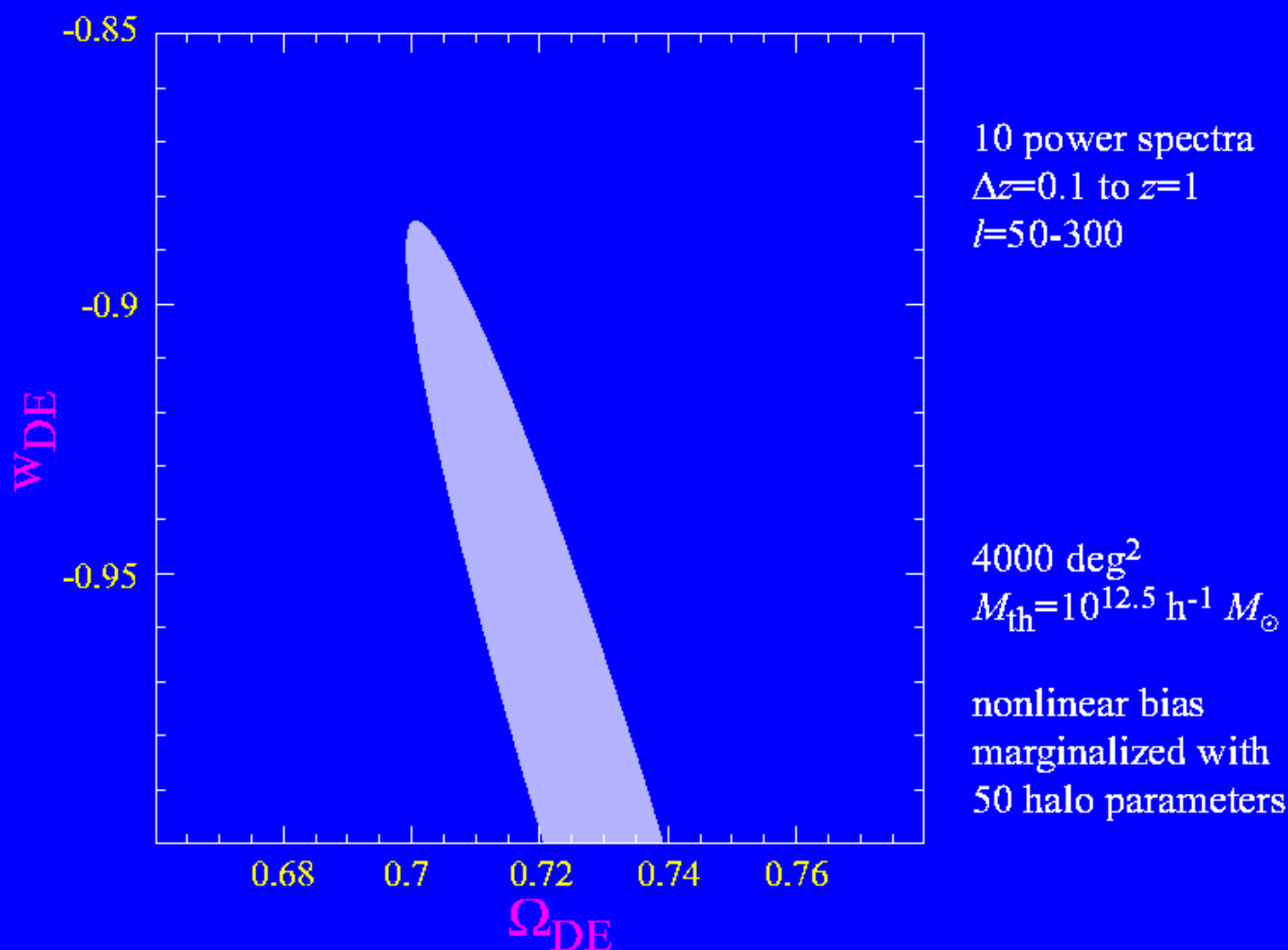SNAP (2366 SNe)
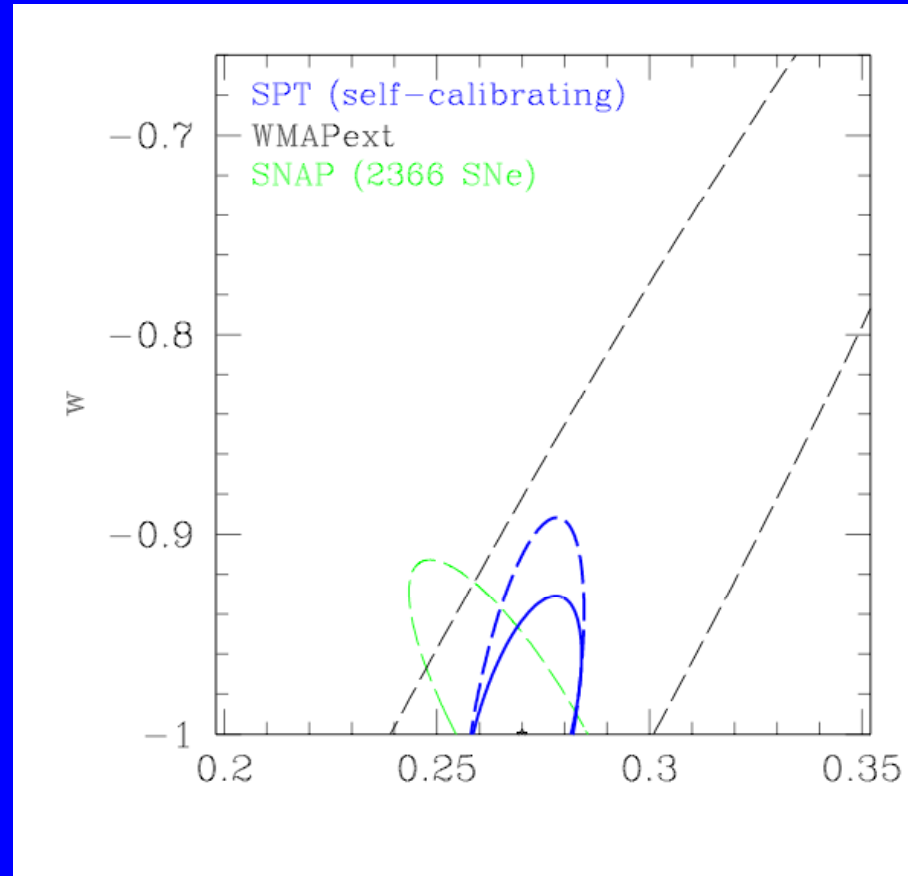
SPT+DES constraints

DES Weak Lensing

- Measure shapes for ~300 million galaxies

- Shear-shear & shear-galaxy correlations probe distances & growth rate of perturbations

- Power spectrum shape det'd by CMB (WMAP→Planck)

Hu
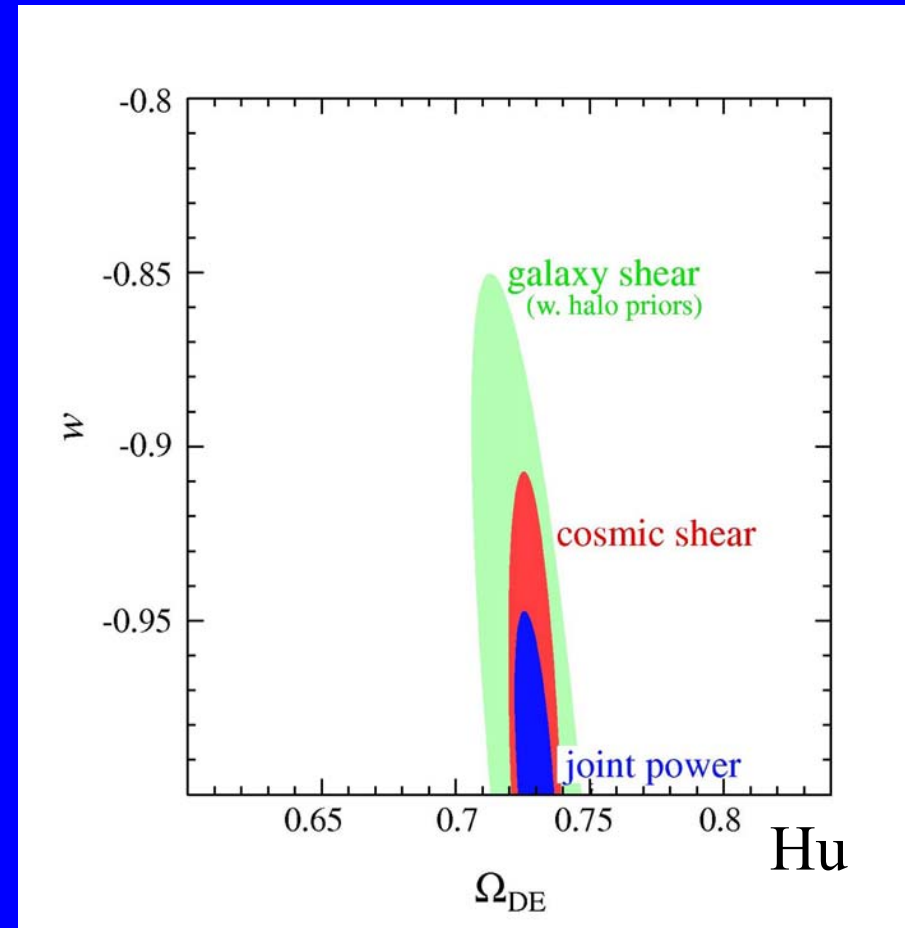
DES constraints

Angular Power Spectrum

- Purely geometric constraint, absolutely calibrated at all z
- Combine with CMB distance $[\Omega_m h^2\ 1\%]$ with constant w

10 power spectra
$\Delta z = 0.1$ to $z = 1$
$l = 50\text{-}300$

4000 deg^2
$M_{th} = 10^{12.5}\ h^{-1}\ M_\odot$

nonlinear bias
marginalized with
50 halo parameters

DES Supernovae

- Repeat observations of 40 deg^2

- ~2000 well-measured SN Ia
    lightcurves at $0.3 < z < 0.8$

- Combination of spectroscopic
    and photometric redshifts

- Develop color typing and SN
    photo-z's (critical for LSST SNe)
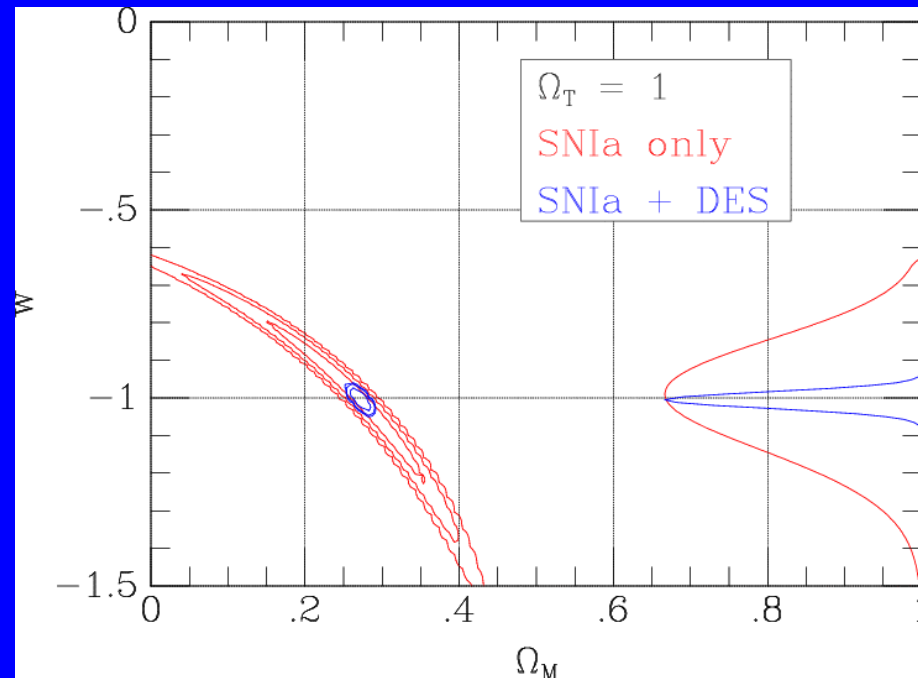
DES constraints

Cluster Abundance

- Self calibration with variance of counts

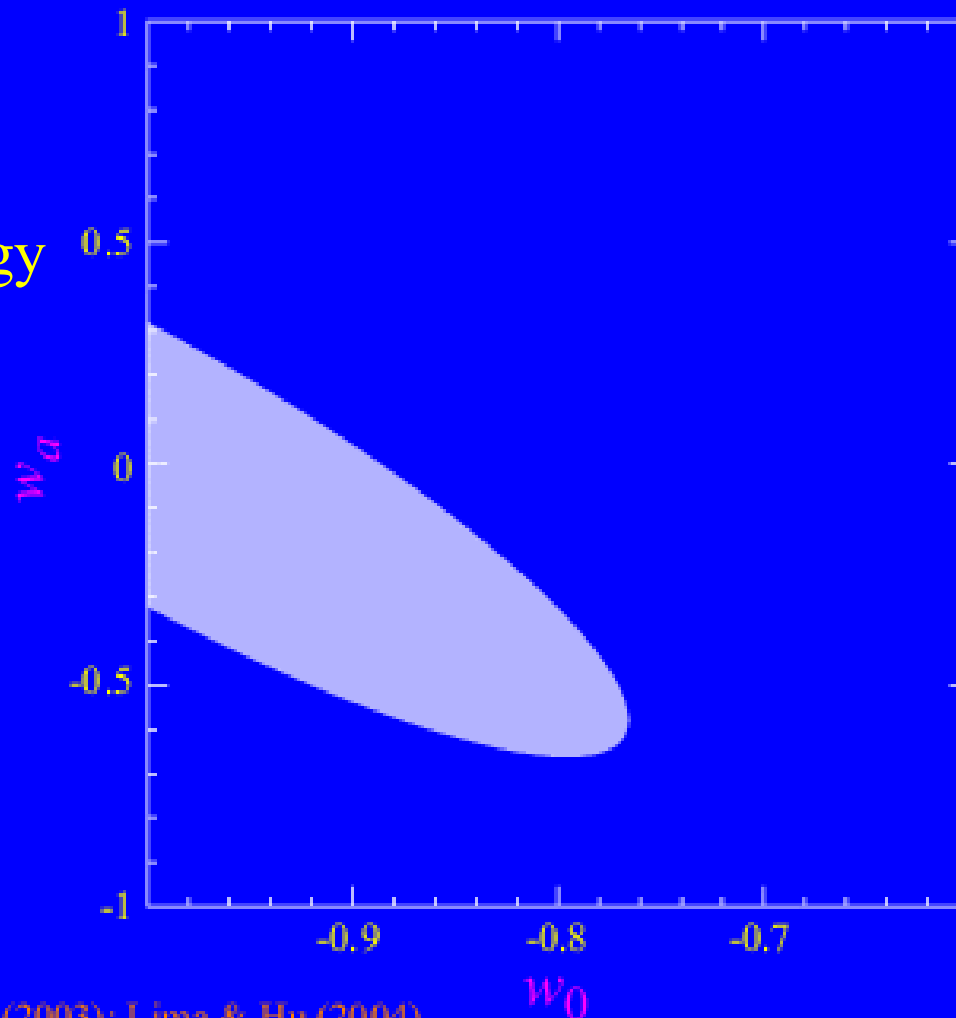Evolution
Of
Dark Energy

10 redshift bins
$\Delta z = 0.1$ to $z = 1$
10 degree cells

4000 deg^2
$M_{th} = 10^{14.2}$ h^{-1} $M_\odot$

Majumdar & Mohr (2003); Lima & Hu (2004)

Galaxy-Shear Correlations

- Galaxy-shear cross spectrum and galaxy-galaxy power spectrum allow for a calibration of galaxy bias hence measure growth

Evolution of
Dark Energy
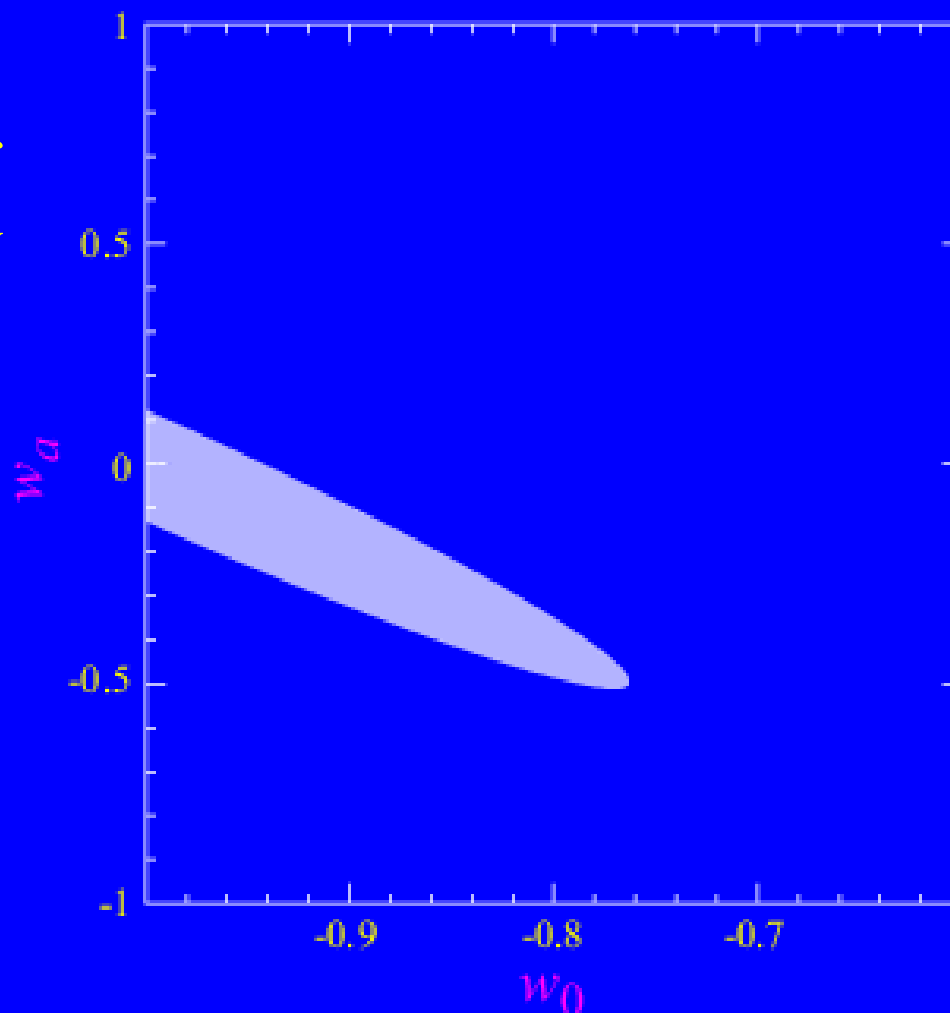
10 redshift bins
$\Delta z = 0.1$ to $z = 1$
$l = 50\text{-}1000$

5 shear bins
$\Delta z = 0.25$ to $z = 1 + z > 1$
$\gamma_{rms} = 0.16$; $z_{med} = 0.7$
n = 10 gal/arcmin^2

4000 deg^2
$M_{th} = 10^{12.5}$ h^{-1} $M_\odot$

nonlinear bias or N(M)
marginalized with
50 halo parameters

Shear-Shear Correlations

- Cosmic shear statistical forecast:

Evolution of
Dark Energy
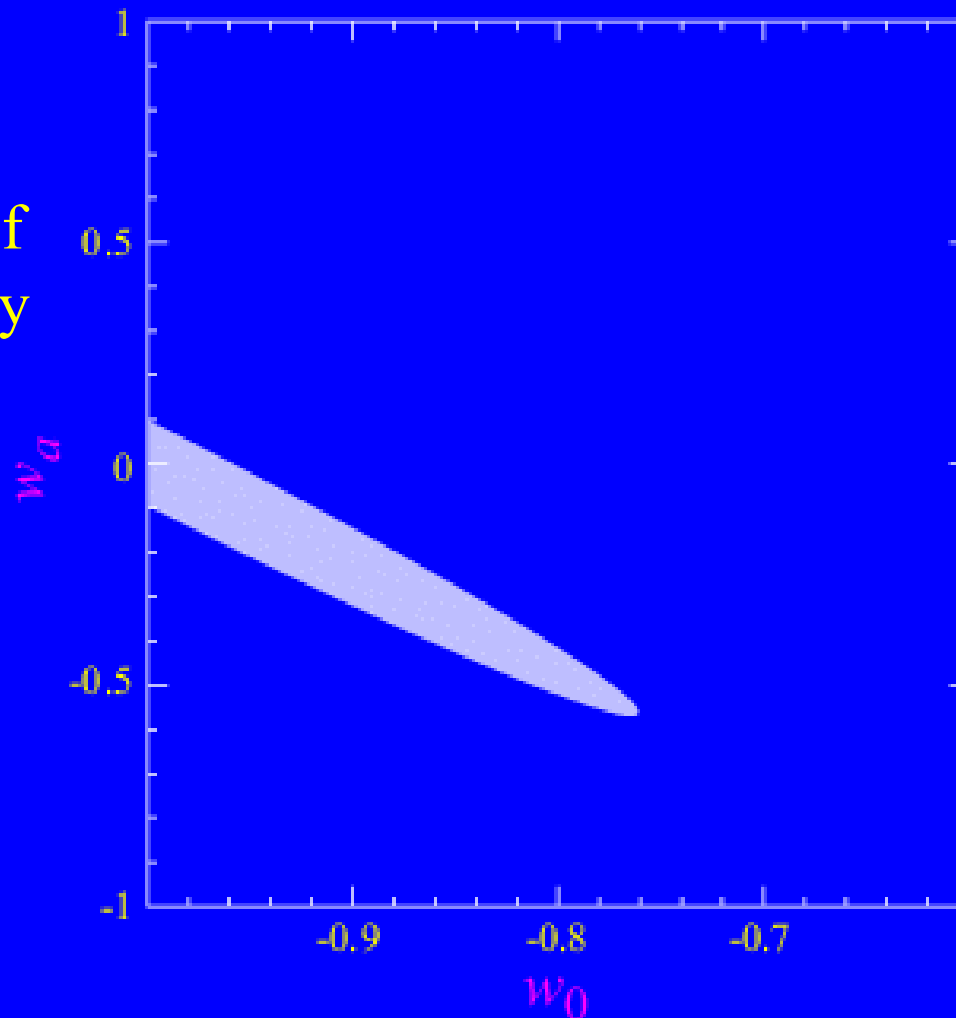
l=50-3000

5 shear bins
Δz=0.25 to z=1 + z>1
γ_{rms}=0.16; z_{med}=0.7
n=10 gal/arcmin^2

4000 deg^2
no systematic floor

Dark Energy: 2013 and Beyond

Ground: LSST   Dedicated 8m telescope with wide FOV imager

with aggressive schedule, first light in 2012   ~several 100 M$

- Space: JDEM   2m optical/NIR wide-field telescope in space

launch date uncertain, 2014?   ~1B$

- Goals: *w* to few %, *dw/dz* to ~30%

- Designed as `ultimate' Dark Energy experiments, they must have exquisite control of systematic errors to reach the next level of cosmological precision

- Timescales and costs reflect this

Dark Energy Survey Schedule & Science Results

- Current schedule: survey begins Fall 2008, driven primarily by desire to rapidly exploit SPT clusters: SPT survey starts 2007

- Survey Strategy aims to produce useful cluster Dark Energy science after ~2 years of operations. Many other short-term science payoffs as well: 1yr will double ESSENCE SN sample; galaxy clustering; galaxy-galaxy lensing;…

- If DES slips 2 years and LSST not at all (unlikely given the relative scales)*, we still have ground-breaking science results two years earlier.

- If LSST is not in Chile, no major competition on the cluster Dark Energy science. If LSST *is* in Chile and DES does not happen, SPT must wait ~7 years for its cluster Dark Energy science.

*assuming schedules driven technically vs. financially

Year	filter	Area	Tilings	Total	Magnitude	Photometric Calibration		Cluster z and weak lensing
		sq-deg.		Int seconds	10σ	Relative %	Absolute %	n_g
1	g	5000	2	200	24.2	1.8	3.5	
	r	5000	2	200	23.7	1.8	3.5	
	i	5000	2	200	23.3	1.8	3.5	
	z	5000	2	200	22.6	1.8	3.5	z= 0.7
								$n_g\sim8$
2	g	5000	4	400	24.6	1.2	2.5	
	r	5000	4	400	24.1	1.2	2.5	
	i	5000	4	400	23.6	1.2	2.5	$n_g\sim12$
	z	5000	4	400	23.0	1.2	2.5	
3	g	5000	5	500	24.7	1.0	2.2	
	r	5000	5	500	24.3	1.0	2.2	
	i	5000	6	700	23.9	≤1	≤2	
	z	5000	6	700	23.3	≤1	≤2	z = 1.0
								$n_g\sim16$
4	g	5000	5	500	24.7	1.0	2.2	
	r	5000	5	500	24.3	1.0	2.2	
	i	5000	7	900	24.1	≤1	≤2	$n_g\sim20$
	z	5000	9	1300	23.6	≤1	≤2	
5	g	5000	5	500	24.7	1.0	2.2	
	r	5000	5	500	24.3	1.0	2.2	
	i	5000	7	900	24.1	≤1	≤2	$n_g\sim28$
	z	5000	13	2100	23.9	≤1	≤2	

Table 1: Survey Strategy

A National Wide-Field Imaging Facility

- Blanco+DECAM will be 2/3 time user facility (100% user after DES), unlike PanSTARRS and LSST: it will be a unique resource for the astronomy community.

Relative Performance

Metrics for comparing facilities:

(a) Faint Time window: $A \, \Omega \, \varepsilon \, / \, \Omega(\text{psf}) \, \tau \, \beta^{1/2}$

(b) Faint stellar: $A \, \Omega \, \varepsilon \, / \, \Omega(\text{psf}) \, \beta^{1/2}$

(c) Faint resolved galaxies: $A \, \Omega \, \varepsilon \, / \, \beta^{1/2}$

where sky noise limited exposures are assumed, and

A = Telescope primary area

Ω = Detector area

ε = efficiency (clouds, readout time, CCD QE, etc)

$\Omega(\text{psf})$ = area of stellar point spread function

τ = cycle time

β = background sky brightness

Relative Performance

Faint Galaxy Performance: $(A\Omega\epsilon / \beta^{1/2})$

LSST: 312

DECAM   (3 deg^2)   15   2/3 facility instrument, will enable
                                     a variety of science programs

PanSTARRS: 15.8 (1 telescope)   63 (4 telescopes)

CFHT Megacam: 2.7

Subaru: 1.4

SDSS: 2.1

VST: 1.4

VISTA (IR):   0.93

CTIO 4m + Mosaic: 0.9